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AN EW PERCEPTION OF REQUIREMENTS FOR MARITIME SENSOR AND WEAPON INTEGRATION

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A. Sewards and B. Barr

DEFENCE RESEARCH ESTABLISHMENT OTTAWA
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ABSTRACT

In order to defend a ship against an attack by anti-ship missiles, it is necessary for the ship to detect the attacking forces, and then to use its entire defensive suite of weapons. These weapons may consist of anti-missile and anti-aircraft missiles, gatling guns, and electronic countermeasures such as on-board jammers, off-board decoys, and chaff. To maximize the probability of detecting and identifying the attacking forces and the missiles launched against the ship, information from all of the ship's sensors must be integrated. Similarly, if the chances of defeating the incoming missile attack are to be maximized, the defensive weapons must be deployed in a sequential and co-ordinated manner, in a layered defence.

This paper discusses the advantages to be obtained from the integration of sensor data and the co-ordination of hard-kill (missiles, guns) and soft-kill (ECM, decoys, chaff) weapons systems. Problems of integration of information from different sensors, the need for a layered defence, the characteristics of the various systems, a typical scenario to illustrate the need for integration, possible architectures and issues that must be addressed are examined. The approach is from the viewpoint of Electronic Warfare, but encompasses all aspects of the sensors and weapons available.

RESUME

Afin de protéger un navire contre une attaque par des missiles contre-navire, il faut d'abord que le navire detecte les forces opposantes, et qu'ensuite il utilise toute la gamme de ses systèmes défensifs. Ces systèmes peuvent inclure des missiles contre-missile et contre-avion, des fusils gatling, et aussi des contre-mesures électroniques comme systèmes de brouillage montés sur le navire, des leurres en dehors du navire, et des plaquettes de brouillage. Afin de maximiser la probabilité de détecter et d'identifier les forces opposantes et les missiles lancés contre le navire, il faut intégrer l'information provenant de tous les systèmes détecteurs du navire. De la même façon, afin de maximiser la probabilité de vaincre les missiles qui arrivent, il faut déployer les systèmes de défense d'une manière séquentielle et bien coordonnée, dans une défense stratifiée.

Ce rapport décrit les avantages qu'on peut obtenir par l'intégration des détecteurs et la coordination des systèmes de défense, comme les missiles et les fusils, avec les systèmes électroniques, comme les contremesures, les leurres, et les plaquettes de brouillage. On examine les problèmes de l'intégration d'information provenant de détecteurs différents, le besoin d'une défense stratifiée, les caractéristiques des systèmes de défense, un scenario typique afin d'illustrer le besoin d'intégration, les architectures possibles, et certaines questions qu'il faut éclaircir. On approche le sujet du point de vue de la guerre électronique, mais en incluant tous les aspects des détecteurs et systèmes de défense disponibles.

"AN EW PERCEPTION OF REQUIREMENTS FOR SENSOR AND WEAPONS INTEGRATION"

EXECUTIVE SUMMARY

Recent events have demonstrated the need for information produced by all the sensors available on a ship to be integrated. Radar provides good accuracy of range and angle of a potential attacker, but cannot give information relating to identification. Electronic Warfare receivers can often detect radar signals from an attacker before the radar can see the ship, and can determine the direction of arrival of the signals and classify them according to type. This classification usually permits the platform type to be derived. Sonar allows detection of surface or undersea attackers and provides direction information, and frequently platform identification. Infra-red systems can make extremely accurate measurements of target angle of arrival. At present, data from all these sensors is not integrated in an effective manner.

Once it has been established that an attack is imminent, the typical warship carries a number of weapon systems that are used in defence. These include hard-kill systems such as anti-aircraft and anti-missile missiles, and close-in weapon systems employing high rate-of-fire guns, and soft-kill systems such as on-board electronic countermeasures (jammers), chaff, and decoys. Present strategy is to deploy these various weapons in what is essentially an uncoordinated manner, which may result in hard-kill systems being used to shoot down missiles which have been successfully decoyed away from the ship by soft-kill systems, or in missiles being decoyed on to a high value target. At the least, there is an unnecessary over-expenditure of expendables, and at worst, the advantages to be gained in having a layered defence are thrown away. Ideally, the defence of the ship should take place in a sequential manner, with each stage of the enemy attack being met with a defensive layer tuned to its vulnerabilities.

For example, in the case of an attack by air-launched missiles, even before the missiles are launched, on-board ECM can be used to generate a large number of false targets in the attacking aircraft's radar, and, at the same time, distraction chaff is widely sown. When the aircraft gets to the point of using its radar for targeting, it is presented with an extremely confusing situation, with a correspondingly low probability of correctly selecting the true target. If missiles are launched, they may be attacked in mid-course by anti-missile missiles. Once they have got close enough to the ship to activate their seekers, decoys, distraction chaff, and on-board ECM can be used to interfere with the target acquisition process. If the missile locks on to the target, ECM, decoys, and seduction chaff are deployed to break the lock and transfer the seeker to a false target. In the last resort, the ship's close-in weapon system (guns) are employed to shoot down the missile. Each stage of the engagement is met with a response which measurably reduces the probability of successful completion of that stage, with the overall result that the probability of kill of the attacking missile is reduced to a very low level.

Properly integrated ship's systems are a prerequisite for implementing this type of layered defence. In particular, it is essential that the commander have available timely and precise information giving position, velocity and type for all target tracks. Without this data, it is impossible to evaluate and prioritize threats, since all targets must be presumed equally lethal. It is impossible to optimize weapons assignment, since there is no basis for assessing threat vulnerability. It is impossible to coordinate soft-kill and hard-kill options, since there is no feedback on soft-kill effectiveness. Without integration, the commander's ability to coordinate and control his ship's self-defence resources is severely degraded, compared with what it should be. He is reduced to crisis management - forced to react at the last minute to threat situations. The result may well be tragic: a ship lost or damaged and lives lost, or a friendly target attacked on the basis of radar measurements, because EW receiver data which could have identified the platform type became available too late to be useful.

It may be asked why, if it is so obvious that large benefits are obtained from integration of sensors and coordination of weapons, this has not already been done. The answer is that a combination of circumstances has prevented it until recently. The most important of these has been the tendency for the various sensors and defensive weapons to be conceived, developed, and produced in isolation from each other, only to be brought together on the ship, and there superficially "integrated". Until recently, the computer architecture employed on ships for Command & Control has tended towards centralized control of separately integrated subsystems with little or no provision for downward control. No attempt has been made to fully integrate data from a number of sensors, largely due to the lack of responsibility for so doing, and inadequate understanding of the details of the various sensors, which is a prerequisite. Validated algorithms for such integration have yet to be developed.

This paper starts by establishing the need for a layered defence, and then discusses the strengths and weaknesses of the various sensors (radar, EW, sonar, and infra-red). Problems in and techniques for the integration of data from these sensors are considered, and an example given. The various defensive weapons available on the ship (missiles, guns, ECM, decoys, chaff,) are then reviewed, together with their capabilities and limitations. It is shown that both soft-kill and hard-kill weapons require feedback from sensors, and special data. Techniques and requirements for weapons coordination are discussed, and followed by sample scenarios, one using hard-kill weapons only, and the second using a full layered defence with both hard-kill and soft-kill weapons. Having demonstrated the value of such a coordinated and layered defence, the paper considers possible architectures for achieving the right connections. A first attempt by the French navy in this direction is briefly described. The paper concludes with a discussion on how to achieve the required capabilities, requirements for flexibility, handling war modes of operation, impact on design of EW, sensor and weapons systems, and requirements for research.

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1.0 INTRODUCTION

The problem of integrating information produced by a number of sensors on a warship, of deciding which of a number of detected targets is a threat, and of using in the most effective manner the resources available of hard and soft-kill weapons has been around for a long time. Until recently, there were few vital sensors and weapons, and manual means were the norm for battle assessment and data integration, and the difficult problem of programming computers to perform the necessary tasks could either be simplified or avoided entirely. With the introduction into service of new threats, demanding rapid response, and new generations of sensor and weapon systems, each containing computers and some capability for integrating information or for operating autonomously, this problem has become much more difficult. In addition, the complexity of the defence capability has been increasing, to the point that few individuals have sufficient knowledge of the capabilities of all the systems on one ship. This makes the job of specifying software to perform the integration function much more difficult, as explicit means must be found and enforced to ensure that all the sensor data and all the weapon capabilities are fully understood and incorporated into the control program.

This paper discusses the advantages to be obtained from the integration of hard and soft-kill weapon systems, the need for a layered defence, the characteristics of the various systems, the problems of integration of sensor information, a typical scenario to illustrate the need for integration, possible architectures, and issues that remain to be addressed before a satisfactory result can be expected.

2.0 NEED FOR A LAYERED DEFENCE

While it is possible to rely on a "last-ditch" stand, using a close-in weapon system (CIWS), to defend a ship against an attack by anti-ship missiles (ASM), the effectiveness of such an approach is highly questionable. If several missiles arrive almost simultaneously, the CIWS may be overwhelmed by numbers. The accuracy of present-day ASMs is such that, if no defensive measures are taken, the missile will surely hit the target, usually at a sensitive place, as it heads for one of the principal peaks of the radar cross section pattern, or a "hot-spot" if an IR seeker. The destructive power of even small missiles in such cases is amply evidenced by the attacks on the *Eilat*, the *Sheffield*, and the *Stark*.

Most warships today are equipped with a variety of defensive systems which fall into two categories: hard-kill and soft-kill. These two types are discussed in more detail in Section 4, suffice to state here that hard-kill systems comprise those, such as missiles and guns which can destroy or permanently incapacitate an incoming missile, while the soft-kill systems (principally Electronic Warfare systems) attempt to jam or deceive the guidance systems of the missiles and cause them to miss the intended target.

If the ship is equipped with several defensive systems, it is important that they be used in the right sequence to reduce the probability of kill of the incoming missiles to the lowest value possible. This must be done with due regard to the effective ranges of the various defences, any interference or synergistic effects between them, and the fact that limited quantities of expendables exist. (Some electronic countermeasures can be used over and over again; chaff, guns and missiles usually are limited by the number of rounds stored.) In practice, this leads to the concept of employing the available defensive systems in a series of layers - the long-range systems are used early in the engagement, followed by the medium-range systems, and finally, short-range systems. This is illustrated in Figure 1, which shows the sequence of operations involved in the air launch of an ASM and the subsequent track to the target ship. At each stage, information is required by the launching aircraft or the missile, and an opportunity is provided for exploiting this requirement to decrease the probability of successfully accomplishing that stage. As the overall probability of kill (Pk) is the product of the separate probabilities for each stage, decreasing the probability of successful completion for each stage by even a modest amount will drastically reduce the overall Pk (Figure 2).

Before the missiles are launched, the attacking aircraft has to locate the target, designate it, and transfer the data to the missile. Target location, in the broad sense, may be done by such means as using ESM to detect radar or communications transmissions from the ship and triangulating on them, by the use of radar surveillance satellites such as RORSAT, or similar means, but target designation is almost always done using radar. For the radar to work, the aircraft must be able to see the ship, and if this is the case, the ship can certainly receive the radar signals with its ESM receivers. Such reception

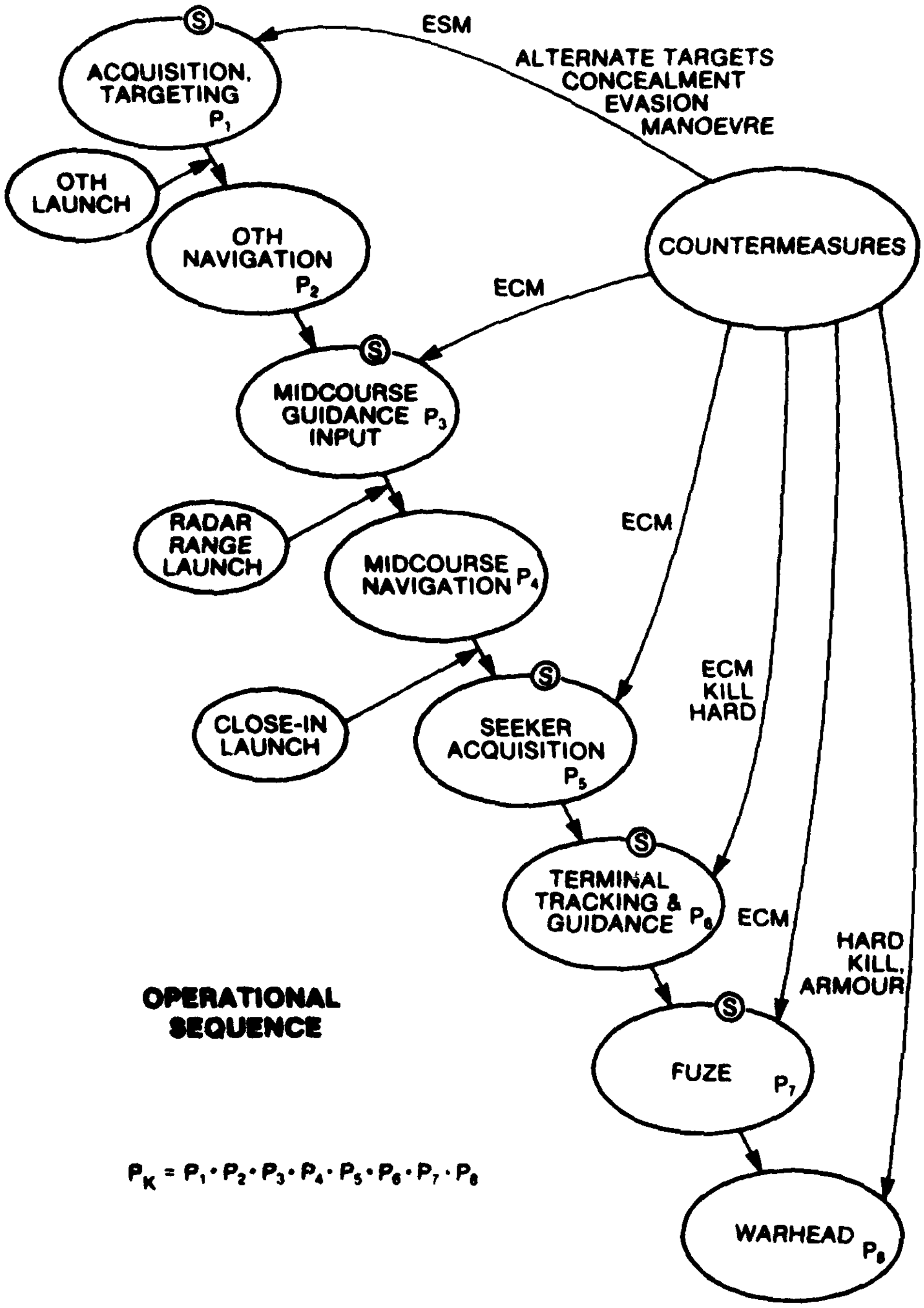

FIGURE 1 SEQUENCE OF OPERATIONS INVOLVED IN THE AIR LAUNCH OF AN ANTI-SHIP MISSILE

LAYERED DEFENCE CONCEPT

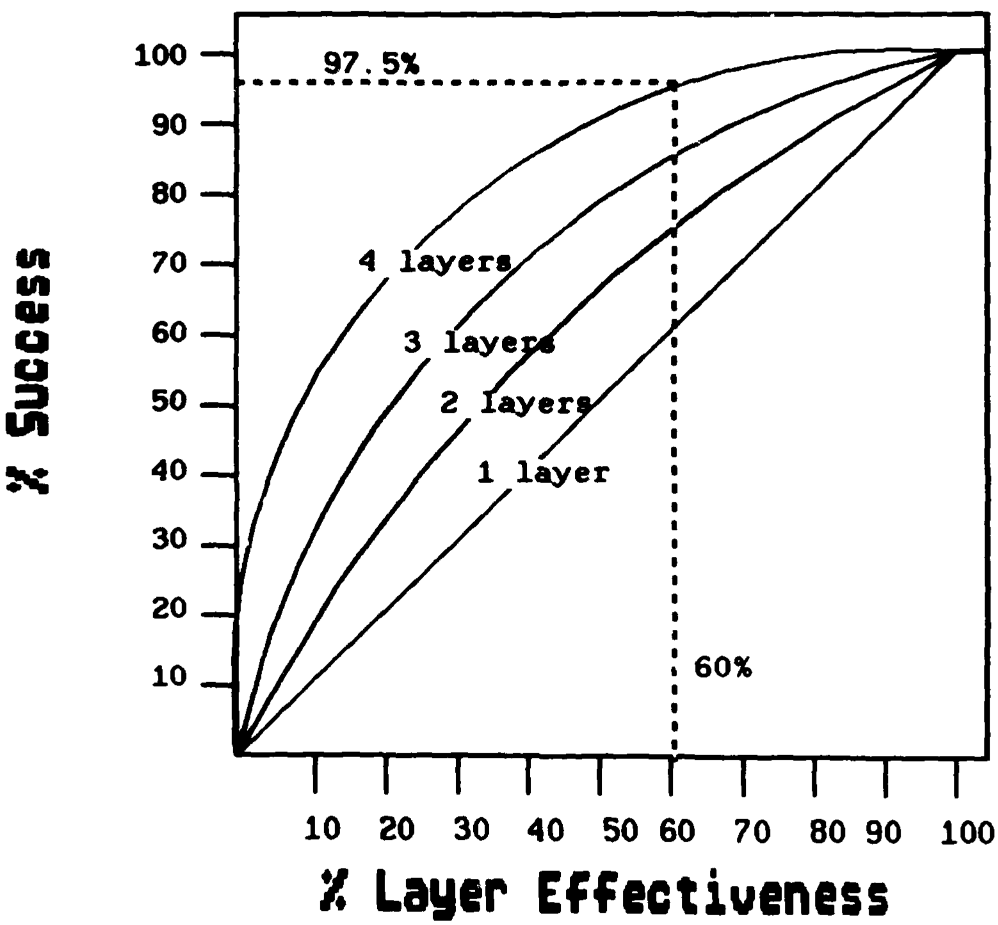

FIGURE 2 CUMULATIVE PROBABILITY OF KILL AS A FUNCTION OF NUMBER OF INDIVIDUAL STAGES

will allow the ship to determine that it is being designated and that missile launch is imminent. Designation can be interfered with by the use of ECM to produce many false targets in the designating radar, by the prior deployment of confusion chaff, and the use of decoys. Once the missiles are launched, they proceed on an over-the-horizon phase, perhaps using inertial guidance. This would afford no opportunity for electronic interference, but physical attack by anti-missile missiles could be attempted, if the range is not too far. A mid-course guidance phase involving an active radar again gives the opportunity for electronic countermeasures in the shape of false targets, chaff and decoys, and also the missile may be at a suitable range for attack by anti-missile missiles launched from the ship. The terminal phase usually involves activation of the terminal seeker radar, search for the target, lock-on, and final homing. As in earlier phases, the search for the target can be interfered with through the use of ECM, chaff and decoys, lock-on can be delayed or prevented through jamming from off-board decoys, and final homing can be broken in similar ways. Finally, close-in weapons can be used when the missile is within gun range. If there are six phases of the engagement, and the probability of success by the missile of successfully completing each one is reduced by the means described above to 60%, the overall probability of success of the missile in striking the ship is reduced to less than five percent.

3.0 SHIP SENSORS

Before an attack can be defended against, it must be recognized. This part involves use of the various ships' sensors, which can include radar, ESM (electronic support measures, or signal detection and classification), infra-red imagers (such as the AN/SAR-8), and sonar. Preliminary information on an attack could come from an external source (e.g. satellite radar, shore-based D/F, tattletale, etc.) or tactical warning (ship-based D/F, airborne sensor). Information from all these sources must be brought together in any integrated air defence system.

3.1 ESM

As mentioned above, first warning of an attack is often provided by the ESM system. If the ship is following an EMCON policy and its main search radar is off to preserve radio silence, the ESM is the only sensor capable of giving long-range detection. The ESM system usually provides the bearing (typically, to a few degrees accuracy) and the electronic parameters of the received signal, and in the case of radar signals, will permit identification by type, in turn giving an indication of the platform and the possibility of related or subsequent actions such as missile launch. Detection of radar signals over-the-horizon is usually possible, and radar signals can be detected before (i.e. at longer range) the radar is capable of detecting the ship.

3.2 RADAR

The main sensor of a ship is generally regarded as being the long-range search radar. This can detect at long range and provide accurate positional information on attacking aircraft and ships, and, in some cases, any missiles that are launched. Accuracy is high - the position of a target can usually be measured to within about 1/2 mile in both range and bearing at the longest range, say 200 miles. More complex search radars can also provide altitude data, typically to within 2000 ft at the longest range. Radar information is provided to the command and control system and serves as the main means of controlling a battle. Other radar sets commonly fitted to warships include navigation radars and fire control radars for guns. These latter can make very accurate measurements of the azimuth, elevation and range of one or a small number of targets being tracked, of the order of milliradians and feet. Long-range missile systems require dedicated radars to provide target acquisition and tracking functions and missile command or illumination. These too, will have accuracies similar to those of fire-control radars. All these functions can be combined in a single multi-function radar (e.g. Aegis), a design trend which is gathering momentum, and is likely to be adopted in future ships.

3.3 INFRA-RED

A class of sensor now coming into service and typified by the AN/SAR-8, is the infra-red imager or infra-red search, track, and target designation (IRST) system. This class of sensor provides an infra-red image of the view as seen from the ship over typically 360 degrees azimuth and 30 degrees elevation. It is capable of very high resolution and accuracy of measurement of detected targets in azimuth and elevation, but cannot, of course, directly provide range data. Range of such sensors depends on the amount of heat emitted by the target, the target/background contrast, and atmospheric conditions, and is limited to the order of 10 miles under good conditions for low-flying aircraft, but may be much longer for hot objects such as aircraft using afterburners.

3.4 SONAR

Not usually regarded as a sensor whose output is to be coordinated with other sensors, the ships' sonar systems are nevertheless capable of providing much useful data for this purpose. Sonars include passive sets, which detect submarines and surface shipping, and occasionally aircraft, through analysis of the sound waves produced by their passage through or close to the water. These sets can provide high accuracy of measurement of the azimuth from which the signal is coming, but range can only be obtained secondarily. Active sonars behave in a similar manner to search radars, and provide accurate range and bearing of any targets detected by them under the surface. Inclusion of sonar data in the integration of sensor data is desirable, as sometimes sonar data could assist in the resolution of ambiguities in identification of a signal received by the ESM system. Passive sonar can detect transient effects such as the launch of an ASM by a submerged submarine, but only under suitable quiet conditions.

3.5 IDENTIFICATION FRIEND OR FOE (IFF)

While usually regarded as part of the radar system, the IFF system produces an output independently of the radar, and can give a positive indication that a target is friendly plus other identification data. It cannot provide positive indications on unknown or hostile targets, as the absence of an IFF return can be the result of a number of factors, such as equipment malfunction or the IFF not being turned on. Under certain conditions, an IFF mode which reports aircraft altitude as well as identification data can be used: however, this is normally only done by civil aircraft.

3.6 OPTICAL TRACKERS

Tracking systems employing lasers or TV trackers have also been proposed and deployed in limited numbers. As a class they possess advantages similar to those of the infra-red imaging systems, of high accuracy of measurement of target angle of approach, and can, in the case of the laser tracker, also provide target range. They also possess the similar disadvantages of relatively short range of operation and degradation by bad weather. A laser tracker, as in the case of radar, provides the attackers with the option of using anti-radiation seekers which can exploit radar or optical radiation from the ship for homing purposes.

4.0 INTEGRATION OF SENSOR DATA

Sensors provide the input to the decision-making process which guides weapons management and assignment. Without timely sensor data, informed decisions cannot be taken, and response times for coordinated hard-kill/soft-kill strategies will be prohibitive. The key pieces of information required by the Command and Control TEWA (Threat Evaluation and Weapons Assignment) subsystem are:

(i) target detection
(ii) target position and velocity
(iii) target classification (e.g. raid size, type of object)
(iv) target identification

Note that we distinguish between classification, e.g. determining from its velocity that the target is a missile, and identification, e.g. determining from ESM intercepts that it is an SS-N-22 or an Exocet.

Table 1 summarizes the capabilities and limitations of the various sensors discussed in Section 3. It is clear that none of the sensors is capable of providing the information required by the Command and Control system to perform its threat evaluation function. For example, radar can reliably detect most targets, but is more range-limited than ESM, while ESM cannot detect targets which do not radiate. An IR system is the most effective sensor against low-flying targets. Only radar can measure target range and velocity accurately. Only ESM and sonar provide target classification and identification. Only sonar can detect underwater threats, and so forth. Each sensor has obvious strengths and glaring deficiencies.

	Radar	IRST	ESM	Sonar
Target Detection	Very good; modern radars can resolve targets in the presence of clutter and jamming.	Good when target is relatively hotter than background. May require long integration times to reduce false alarms from background clutter.	Very reliable detection of radiating targets. No capability if target does not radiate. May degrade in dense signal environment.	Dependent on acoustic propagation underwater and background noise levels.
Target Position and Velocity	Very good; multipath causes elevation measurement errors for low-flying aircraft and missiles.	Very accurate azimuth and elevation measurements (in the order of milliradians). Velocity may be inferred from IR intensity. No range.	Usually provides bearing only to few degrees accuracy. Better azimuth and elevation achievable but costly. No velocity or range information.	Accurate azimuth measurement, but good range estimates only available from active sonar.
Target Classification	Limited; some information can be deduced from target position and velocity. Future systems may use SAR/ISAR techniques to classify targets.	Limited; some information can be inferred from position and velocity. IR imaging systems can provide target profile at close range.	Good; automatic classification of intercepts provided in most systems. Radar function and mode can often be inferred, may need operator intervention.	Good; usually requires operator intervention with current systems.
Target Identification	None with presently fielded equipment.	None with presently fielded equipment.	Good; any targets which are in the ESM emitter library will be identified. Ambiguities due to threat parameter overlap and war modes will degrade performance.	Good; usually requires operator intervention with current systems.
Sensor Range	Good; detections up to 200 miles, although horizon limited for low-flying and surface targets.	Limited to about 10 miles for most targets of interest; longer ranges for high flying hot targets. Severely degraded in fog and rain.	Very good; ESM typically has a significant range advantage over intercepted radars. Over the horizon detection is usually possible.	Fair; long range detection is sometimes possible, but propagation anomalies create "blind" regions.
Other Comments	Not available under EMCON conditions. May be degraded by hostile ECM, but still the primary sensor for self-defence.	Range limited, but easily the most effective sensor against non-radiating low-flying targets.	The sensor most likely to provide first warning of impending attack. Largely automated functions result in excellent response times.	The only other sensor besides ESM currently capable of providing reliable classification and identification of targets.

TABLE 1 SUMMARY OF SENSOR CAPABILITIES AND LIMITATIONS

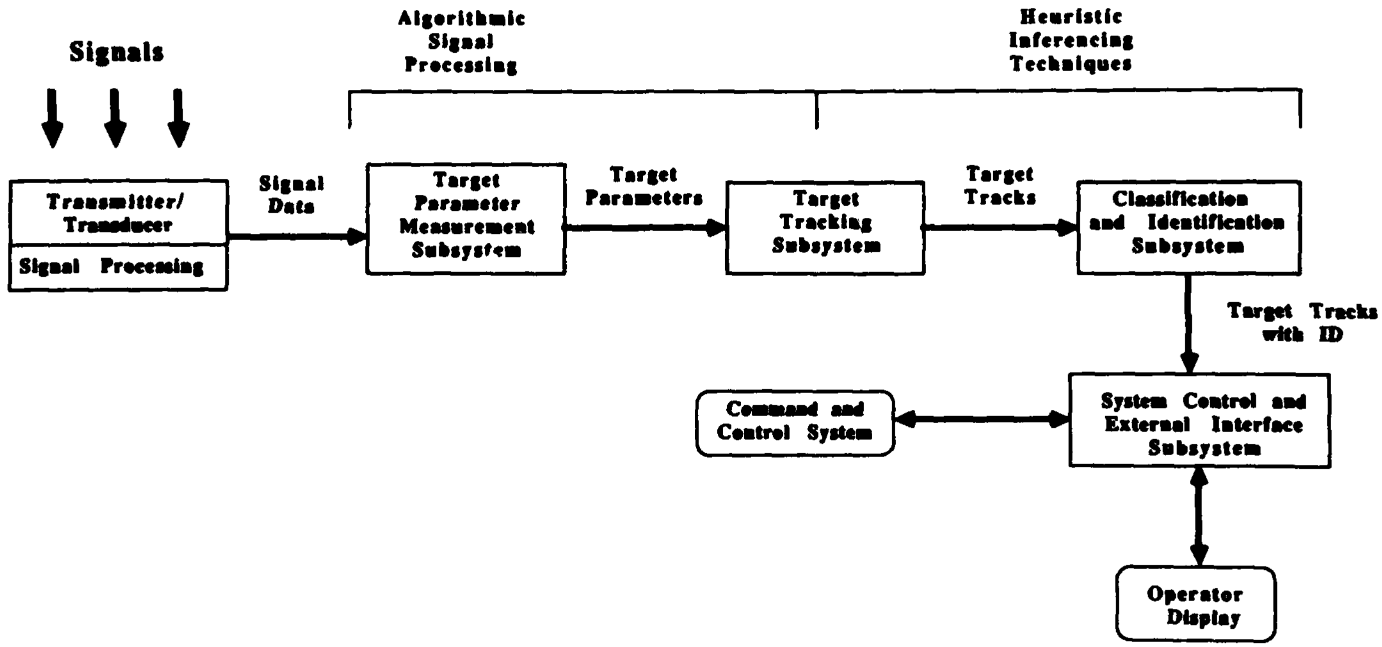

FIGURE 3 GENERIC SENSOR SYSTEM

However, a closer inspection reveals that, collectively, the sensors may well be able to provide all of the information required for the TEWA function, and in a timely manner. Of late, the need for multiple sensor integration, that is, fusing (combining) information from different sensors in some "intelligent" way, has become so widely accepted that the underlying operational requirement is often not considered. The danger is that when the inevitable compromises required to implement such a system are made, wrong choices will be taken because the underlying goals are not clearly understood. As the discussion in the previous paragraph makes clear, the requirement for sensor integration on surface ships is driven by the weapons management problem. It is a prerequisite for threat evaluation and weapon assignment that the target be detected, tracked, classified and identified. Since no one sensor is capable of performing all these tasks, an integrated sensor suite is mandatory. Unfortunately, as we shall see in the remainder of this section, true sensor integration is a thorny problem not easily addressed by simplistic solutions.

4.1 GENERIC SENSOR MODEL

Figure 3 illustrates a block diagram for a generic sensor. All sensors receive signal data (which they may generate themselves if they are active), and, using appropriate signal processing algorithms, measure some set of target parameters. A target tracking subsystem is usually included which groups signal data with similar parameters and provides some indication of parameter change over time. Based on this track (i.e. grouped parameter data), the system tries to infer other attributes which can be used to classify and identify the target. Nearly all sensors employ standard signal processing algorithms (e.g. averaging, autocorrelation, alpha-beta trackers, Kalman or extended Kalman filters) for parameter measurement and some tracking functions.

Heuristic inferencing techniques are typically used for classification and identification, and may be used to perform tracking functions when there is insufficient data for classical signal processing. Examples of heuristic techniques include having the sensor operator perform some or all of the classification and identification functions, or using lookup tables. The next generation ESM and sonar systems, on the other hand, will likely use artificial intelligence techniques to perform these functions automatically, or at least provide the operator with an expert system which serves as an "intelligent assistant".

4.2 BASIC INTEGRATION CONCEPTS: VISUAL FRAMES

Based on this generic sensor model, we can state that integrating data collected by disparate sensors involves two distinct but related issues: track correlation, and target classification and identification. Track correlation must necessarily precede any attempt to merge classification and identification information. Each sensor has what might be called a visual frame, i.e. those parameters or attributes of an object which the sensor can "see" and measure. All target parameters which a sensor measures (its entire visual frame), as well as any attributes it can infer, can be brought to bear on the classification and identification problem. However, when correlating track data from two or more sensors, only the measured parameters which are common to each sensor's visual frame will be useful.

Consequently, track correlation proceeds by refinement, as common features of the target in the visual frames of the sensors are compared. Results will almost always display some ambiguity due to parameter measurement errors. Fortunately, because this information is typically processed using

classical signal processing algorithms, errors can usually be described statistically. Hence it seems likely that (as with the generic sensor itself) algorithms based on standard techniques for combining this information could be developed. The problem is still not easy: for example, to list only a few sources of measurement error, uncertainty is generated by misalignment and boresight errors, ship flexure, false alarms, and differences in sensor resolution (a multi-dimensional issue, e.g. radar may be able to measure position more accurately than ESM, but ESM may be better able to measure raid size thanks to its resolution in the frequency domain).

Target classification and identification, on the other hand, is an *aggregating process*. The entire visual frame plus the inferred attributes contributed by each sensor can, in principle, be brought to bear on the problem. However, the inferred attributes, provided mainly by sensors such as ESM and sonar which have a classification and identification capability, tend to be ambiguous and do not lead to unique answers. Quantifying this uncertainty is difficult, since, as we have seen, these inferred attributes are typically derived from heuristic inferencing techniques (such as operator knowledge or lookup tables) and not by statistical methods. Most of the attempts at characterizing the error introduced by heuristic algorithms (e.g. Shafer-Dempster theory, Bayesian networks, certainty factors, truth maintenance systems) have deficiencies. At this time it appears that further research is necessary before fully automated systems are feasible.

4.3 LEVELS OF INTEGRATION

The term *sensor subsystem* will be used to denote the individual sensor systems together with that part of the Command and Control system which deals with sensor input and sensor integration. We recognize that some Command & Control systems may not be partitioned in such a way that the sensor-oriented functions are contained in modules separate from the rest of the system. Nonetheless, the terminology is useful when discussing sensor integration. The reader is cautioned, however, that the discussion which follows deals with abstractions: when we refer to a Track Correlation function in the Sensor Integration Subsystem, we are not implicitly describing any particular implementation. This function could be entirely contained within the Command and Control System, distributed amongst the sensors, or some combination of the two approaches could be taken. When it is intended to limit the discussion to a particular implementation, we will do so explicitly.

Three levels of integration appear to be possible for the sensor subsystem:

(i) Complementary integration: Each sensor operates autonomously. Information flows one way from the sensors to a central Sensor Integration Subsystem; any merging of information is done there. Sensors are engineered so as to be mutually non-interfering (e.g. high PRF radars should not capture ESM channels). With this model, it is difficult to imagine that the Sensor Integration Subsystem could merge classification and identification data without detailed knowledge of each sensor's signal processing algorithms and techniques. Changing a sensor would likely require extensive changes in the Command and Control system as well. We describe the sensor

operations at this level as complementary, in the sense that we do not expect the performance level of any given sensor to improve as the result of integration, but we hope that collectively they can make up for each other's deficiencies. In terms of information flow, we have a monologue rather than a dialogue.

(ii) Partial synergistic integration: The basic capabilities are augmented so that sensors can be tasked by the Sensor Integration Subsystem to actively seek out and provide data for specified tracks as well as operate autonomously. Information derived from one sensor can now be used to "cue" another. Examples of such cues are an ESM or IRST making first contact with an incoming missile and directing a multifunction radar immediately to the correct bearing. This effect is often referred to as synergism, i.e. sensors can be directed to act cooperatively so that the net result is greater than the sum of the parts. Integration centers mainly on reducing track correlation errors. Information flow now appears as a dialogue, but it is a limited dialogue focused on the track correlation problem.

(iii) Full synergistic integration: Sensors become "intelligent" agents which can interact cooperatively with each other and the Sensor Integration Subsystem as a whole at the level of tactical information exchange, i.e. they can discuss both track correlation and classification and identification of targets. Intuitively, this requires close coupling between sensors and the Sensor Integration Subsystem. The TEWA can calculate engagement solutions based on multisensor data, and sensors can be tasked (via the Sensor Integration Subsystem) to support the weapons control subsystem (e.g providing kill assessment information, or cues to the ECM subsystem).

The challenge with full integration is two-fold:

(1) structure the data flow so as to ensure the maximum exchange of useful information with the minimum data transfer.

(2) provide close coupling between the sensors and the Sensor Integraton Subsystem without losing modularity, i.e. it should be possible to change or upgrade a sensor without making wholesale changes to the command and control system as well.

We will continue our discussion of these issues in section 7.

4.4 EXAMPLE USING SEVERAL GENERIC SENSORS

We will conclude this section with a more concrete discussion of the key issues using some of the generic sensors discussed in Section 3 (SHIP SENSORS) as examples. As illustrated in Figure 4, three sensor systems are considered (radar, ESM, and IRST), together with a Sensor Integration Subsystem. The Sensor Integration Subsystem consists of a Track Correlator and a Track Identifier.

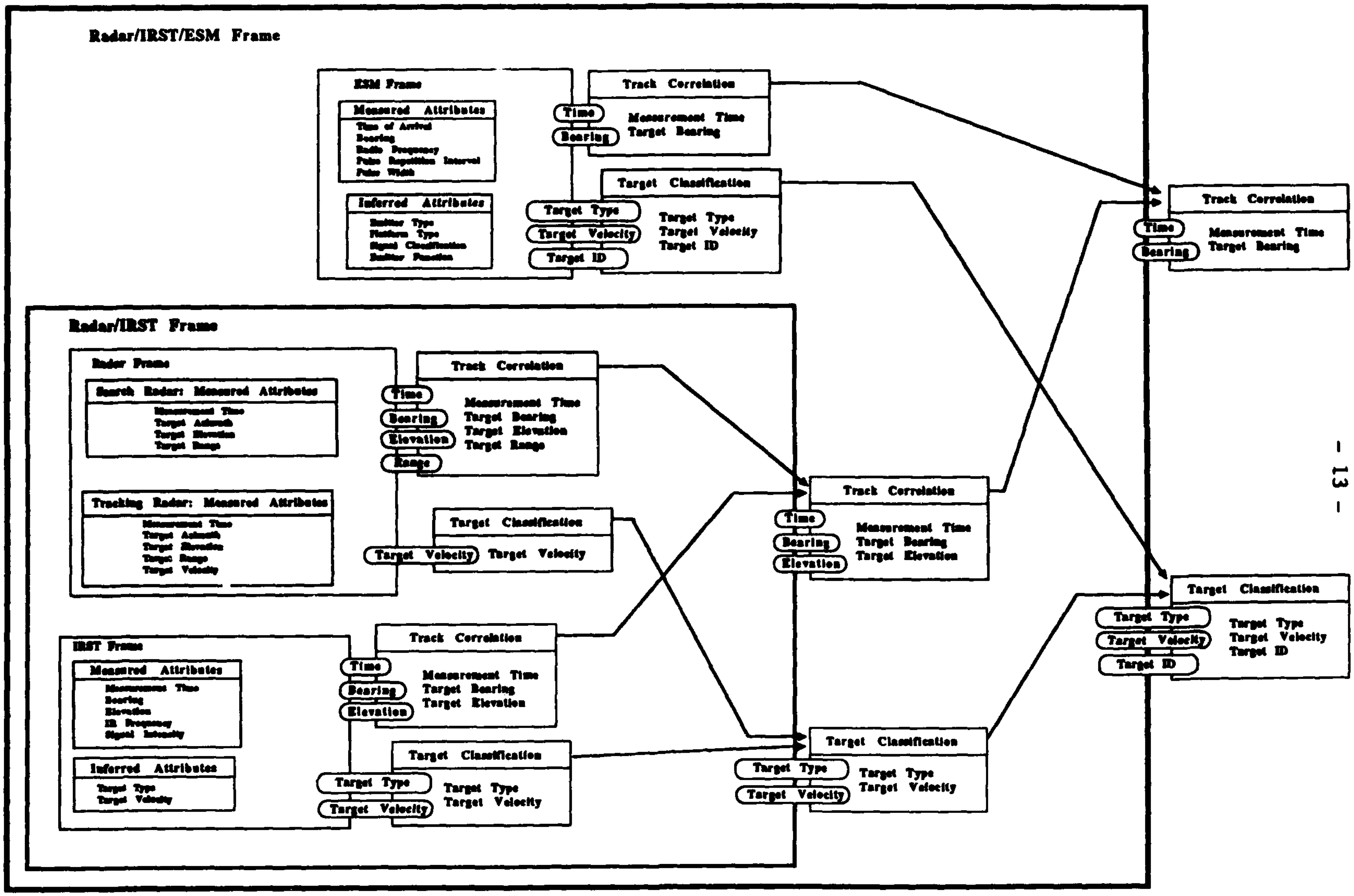

FIGURE 4 SENSOR INTEGRATION

As was indicated above, track correlation between several sensors is based on combining target attributes common to the sensors' visual frames. In our example, position and velocity are the common attributes. Within the radar frame, position data from several radars can be combined using all positional parameters: time, bearing, range, elevation, and possibly velocity. When combining information from the radar and IRST frames, range and velocity will no longer be available parameters. Finally, when integrating ESM with the radar and IRST frames, time, bearing, and perhaps elevation measurements are the correlating parameters. This suggests that sensor data should be combined hierarchically, i.e. data from sensors whose fields of view overlap extensively should be combined before that from sensors whose fields of view have little overlap.

We continue the example by considering the following simple scenario. We assume that the radar has detected three targets, that the IR system has detected two targets in the same azimuth and elevation plane, and that ESM has also detected three targets in the same bearing sector. Each ESM intercept has associated with it three possible identifications, i.e. three possible emitter/platform pairs from the ESM library.

In this example, one can think of the result of track correlation and identification as a set of associations between a radar track and an ESM track, an ESM identification, and an IR track, together with some measure of belief or confidence that the association is correct. For example, we could represent a particular track correlation as:

R1 > ((E1,ID12), I1, Bel)

which is interpreted to mean that the radar track R1 has been associated with the ESM track E1, the second ESM identification for that track ID12, and the IR track I1, with a belief or probability Bel.

In effect, the job of the Track Correlator and Track Identifier algorithms is to compute those beliefs for each possible association. As suggested, the best approach is probably to attack the problem hierarchically: if it can be shown, for example, that R1 and I1 cannot be correlated, then we can eliminate any associations containing both of these tracks. Once tracks in the different visual frames have been correlated, other measured attributes such as target type and velocity can be used to classify and identify them. In our example, we will need to compare target attributes provided by ESM identifications with the classification data (e.g. velocity and IR intensity) collected by the radar and IR systems.

To get some sense of the computational complexity involved in merging sensor data, it is worth noting that in our simple example there are 1648 possible radar track to identification associations! Experience with ESM ambiguity analysis suggests that in a typical case a significant fraction of these associations will have a positive belief (i.e. be plausible) and cannot be discounted without some fairly deep analysis. It does not seem farfetched to suggest that for a realistic multi-target situation such as a coordinated missile attack against a convoy, a simplistic approach to the sensor data fusion problem might well fall victim to combinatorial explosion, even if it was logically correct.

One is led to conclude from this simple example that the task of finding good algorithms for multi-sensor integration will probably be a difficult one, with both logical correctness and computational complexity being important issues. Certainly, most current examples of sensor integration (e.g. typical ESM to ECM interfaces) do not really fuse the data; rather one sensor provides a parametric cue to another, which then autonomously reacquires (hopefully) the same track. These systems are easily confused when two targets with similar characteristics appear in the sensors' visual frames.

On the other hand, there are a number of approaches and techniques which seem promising for developing truly synergistic fusion algorithms. The use of layers or hierarchies has already been suggested. The concept of visual frames could be elaborated to define a language for inter-sensor communication. This could be further extended to include intelligent modules in the Sensor Integration Subsystem.

5.0 SOFT-KILL AND HARD-KILL WEAPONS

Warships are usually equipped with two general types of weapons for self defence - the more obvious traditional hard-kill weapons such as guns and missiles, and the less obvious, equally effective, but often more cost-effective weapons such as electronic countermeasures, sometimes known as soft-kill weapons. In this section, the different properties of these two classes of weapons will be discussed and compared, leading to consideration in later sections of how they can best be integrated and used to maximum effectiveness.

5.1 SOFT-KILL WEAPONS

Soft-kill weapons is taken here to apply to the Electronic Warfare techniques of chaff, decoys and electronic countermeasures (ECM). The emphasis is on methods which achieve the goal of preventing the incoming missile from striking the ship without actually damaging or destroying the missile. Thus we exclude directed energy weapons from the category.

5.1.1 CHAFF

Chaff is one of the oldest means for generating false targets in radar systems. It consists of bundles of tiny aluminized glass dipoles which are lofted to the desired dispersal point by means such as rockets or projectors, and then dispersed by a small explosive charge. Within a few seconds, a cloud of dipoles forms, which returns a radar echo comparable with that of the ship, and which is blown by the wind and hence travels at about wind speed and direction. Careful launching is required to place the chaff in a position where its subsequent motion due to wind results in effective decoying of the interrogating radar.

Despite many predictions of its early demise, due to new discrimination techniques, chaff continues to be effective in many situations, principally because it produces a substantial false target elsewhere than the real target. Used in conjunction with other EW techniques and manoeuvres, it is expected to continue to be effective in varying degrees in the future. The principal ways in which the radar echo from a chaff cloud differs from that of a ship are in the frequency spectrum and the probability distribution of the signal, and in its spatial extent. Despite much study, no means has been found to make chaff echoes closely resemble ship echoes in these respects. It should also be noted that reliable discrimination of chaff from a ship through these parameters without loss of probability of kill has proven elusive. However, as RCS reduction techniques are applied to ship design resulting in the elimination of large discrete scatterers, the ship RCS is expected to become more chaff-like, and this will contribute to an extension of life of chaff techniques.

5.1.2 DECOYS

Decoys, off-board of the ship to be protected, have been considered for a long time, but are only recently becoming reality. Decoys have become popular simply because they offer the possibility of creating a target return which can be made identical to that of a ship, and thus is immune from discrimination techniques. The decoy consists of a platform which can be displaced to the required physical location away from the ship, and which contains either passive means of enhancing its radar cross-section, or an active repeater. Decoys have been proposed or built which float on the sea surface; are towed behind the ship, either on the surface or lofted by kite or autogyro; are contained in a remotely-piloted vehicle, either flying or rocket-sustained; or descend on a parachute after being lofted into place by a chaff launcher.

Corner reflectors or luneburg lenses are popular passive means of enhancing radar cross-section, active means usually involve a travelling wave tube (TWT) repeater or a smart jammer. While passive decoys can be made relatively inexpensive (comparable with chaff rounds), active decoys up to now have all been costly, partly because of the vehicle, but mostly because of the TWT and associated electronics.

5.1.3 ELECTRONIC COUNTERMEASURES

On-board ECM has been in use since World War II. Present day systems are capable of performing noise jamming, deception jamming, and seduction jamming. Noise jamming can be used to obscure sectors of attacking aircraft radar screens, thereby making target designation difficult. It is not normally used against missiles, as present day missiles can home effectively on jamming. Deception jamming is used to produce numbers of convincing and consistent false targets, for preventing either target designation or missile lock-on. Seduction jamming is a form of deception jamming employed against missile seekers, which aims to break the missile lock on to the target in range, and preferably, in angle. When lock has been transferred to the false target, it can either be hooked on to a physical decoy, or dropped, forcing the missile to reacquire the target. Reacquisition is then made difficult

through a combination of deception jamming, chaff, and decoys. The reacquisition process, especially if the ship is outside the radar field of view, consumes valuable time, and may result in the missile being unable to reacquire the original target.

The paragraph above on ECM mentions the distinction , originally expounded in Chapter 2, of the various stages at which attacks can be countered by the defences. Before the anti-ship missile has even been launched, soft-kill weapons can be used to minimize the probability of it being targeted correctly. This is done through the generation of false targets consisting of chaff, decoys, and electronically-generated deception signals. Relatively large numbers of these can be produced, reducing the gross probability of targeting the real ship with the missile to a few percent. After missile launch, ECM can be used to interfere with mid-course guidance, if radar or command guidance is used. In the terminal phase, when the missile terminal seeker is activated, searches for and locks on to a target, and then homes in until impact, the full range of soft-kill weapons can again be employed. Chaff and decoys are used to provide alternate targets and will reduce the probability that the seeker will lock on to the ship, as will deception signals from the ECM. If lock-on is achieved, ECM seduction, seduction chaff, and decoys can be used, singly or in coordinated combination, to transfer lock off the target. A decoy radiating noise jamming can capture a seeker by forcing it into home-on-jam (HOJ) mode.

5.1.4 COORDINATION OF WEAPONS

It is clear from the foregoing that effective use of the soft-kill weapons requires very close control of their deployment and use. Chaff that is improperly placed can attract a missile, which will pass through the chaff cloud and then strike the ship, or strike the ship on its way to the chaff cloud. Seduction techniques can divert a missile from its intended target, only to see it lock on to and hit one of the other ships of the group. For the various techniques to be effective, adequate data must be available at each stage of the engagement, and must be processed in real time and used to determine the next action. In practice, this means that ESM data must be continuously provided to the controlling computer, augmented by radar or other sensor data (e.g. IRST), with chaff and off-board decoys deployed, and on-board ECM used tightly coordinated in the optimum manner for the particular geometry and circumstances of that engagement. Another difficult problem is that of mutual electromagnetic interference. Transmissions from on-board ECM and off-board decoys can blind own ships' ESM and multi-function radars, and be picked up by own and other ships' sensors and interpreted as new threats. High duty cycle ship defence radars can blind ESM, and ECM can interfere with hard-kill weapons control. Careful coordination between sensors and such resources is essential if these potential problems are to be avoided.

Probably the most difficult aspect of soft-kill weapon use, particularly in a situation with many friendly ships close together, is that of hand-off. EW weapons, by their nature, do not disable the attacking missile, they seek to cause it to miss the intended target. If the target ship is all alone in a large part of ocean, this causes no problems, as the missile will fall into the sea a few seconds after missing its intended

target. If the target ship is a member of a force group, the decoyed missile may wreak more damage elsewhere than if it had hit its original target. It is therefore vital that soft-kill weapons be used with a knowledge of the placement of other ships, as well as chaff and decoys launched by own ship.

5.1.5 FEEDBACK

A notion implicit in the operational sequences mentioned above is that of feedback. In order to carry out the successful seduction of a missile, it is necessary to be able to detect the effect the countermeasures being applied to the missile is having. If the decoy or chaff has successfully attracted the missile away from the ship, no other techniques need, or should, be used, as they may negate the decoy or chaff. Conversely, if the decoy or missile has not been effective in attracting missile lock, some other measure needs to be taken immediately. Thus the controlling system needs to have continuing feedback as to the effectiveness of the measure being taken. The changes in missile position, heading, doppler, or strength of signals that indicate this are small, subtle and change slowly, and are thus difficult to measure. This is particularly true for new threat types which are trajectory agile, where the intended target may not be obvious until a late stage of the engagement. In this respect, the soft-kill weapon is quite different from the hard-kill weapon, where there is often no doubt when the weapon has been effective.

5.2 HARD-KILL WEAPONS

Hard-kill weapons include missiles, guns, and more modern concepts such as directed energy or beam weapons. The object is to damage or destroy the incoming missile or aircraft before it can do harm to the ship. This is usually done through physical damage, by explosion shock wave, impact with fast-moving particles or shells, etc. To be effective, such weapons must come very close to their target, miss distances of the order of feet are required. To achieve this, guns are associated with accurate but short-range tracking radars, which track both the incoming missile and the projectiles fired at it, and continuously correct for any aiming errors. Effective ranges of such weapons are only a few thousand yards, meaning that they are, in most cases, last ditch defences. Anti-missile missiles similarly require very high performance, and rely on radar guidance to bring them close enough to the target to kill it. This is still a very challenging feat, especially with sea-skimming missiles, and will become more so, as missile speeds increase. Future anti-missile systems may be able to use infra-red homing to avoid problems of radar tracking of high-speed low-flying targets.

5.2.1 GUNS

Guns require accurate information for effective operation. Time is usually short, and the guns must be brought to bear as soon as the target gets within range. The ship's radar system can give an initial position to the CIWS, from which it can institute its own search process, detect and locate the target, and then track and engage it. The ship's ESM system could also give a line of bearing to the CIWS, as could an IRST system. The more accurate the data, the quicker the target can be acquired, and in a process where seconds are vital, this is important.

5.2.2 MISSILES

Anti-missile missiles have the same requirements for accurate and timely information for target acquisition. As they tend to work at longer ranges than guns, and have special requirements relating to the need for the missile to be launched vertically or at a high angle and then 'gathered in' by the guidance system, time is just as important.

5.2.3 FEEDBACK

As in the case of soft-kill weapons, feedback on the effect of a deployed weapon is required. Normally, this is very obvious, visually there is an explosion, and the radar echo of the threat will disappear. In such a case, no further action would be taken. It may happen that a missile attack on an incoming missile will deflect the latter but not destroy it. If this happens, the situation will be similar to an engagement with a soft-kill system, and it is necessary to monitor the path of the threat missile to determine whether it still poses a threat and must be engaged by other defensive systems. The points made in para. 5.1.5 regarding trajectory-agile threats apply here also.

5.3 DATA REQUIREMENTS

Both soft-kill and hard-kill weapon systems require data in order to operate. On-board ECM systems usually require data from the ESM system to allow rapid acquisition of the victim emitter: this includes the bearing, and electronic parameters such as pulse repetition frequency, pulse width and frequency, if available. For the effective deployment of chaff, knowledge of the direction of arrival of the threat is essential, together with wind direction and speed. It may also be possible to exploit knowledge of the radio frequency band of the threat by deploying chaff cut to that frequency band. Off-board decoys, which contain electronic means of radar echo enhancement or active jammers, require electronic set-on data similar to that needed by an on-board ECM system, and also require information on wind direction and speed.

Missile defences are deployed on command based on information from a tracking radar system located on the ship. Required data includes bearing of the target and range. Close-in weapons systems such as Phalanx, which employ high rate-of-fire guns, usually include their own radar search and tracking systems, which are capable of autonomous operation once enabled. Normally, they would be supplied with target bearing and range data from the ship search radars.

5.4 COORDINATION BETWEEN SOFT-KILL & HARD-KILL WEAPONS

Because they operate at very different ranges, there is normally little need for coordination between AMMs and CIWS. At longer ranges, incoming threats will be engaged with AMMs. Any missiles that are still threatening the ship at CIWS range will be engaged by the CIWS.

The principal motivation for this coordination is to maximize the use of soft-kill weapons when their effectiveness is high, thereby minimizing useless expenditure of missiles and guns rounds, of which only limited quantities exist. Hard-kill weapons must be used against threats such as ARMs, unless turning off the ship's radars can be accepted. Some threats may be approaching from a direction where chaff or on-board ECM is of limited effectiveness (e.g. a broadside attack from short range, where the high RCS of the ship cannot be reduced in time through manoeuvres), and hard-kill defence is the only one likely to work in time. False target jamming and distraction or counter-targeting chaff is highly effective in avoiding targeting before missile launch. Judicious use of ECM, chaff and decoys can greatly reduce missile Pk in the transition from mid-course to terminal guidance. Ship manoeuvre can also be employed as a soft-kill asset, for those cases where there is sufficient time. When used in concert with other techniques, manoeuvre can further increase survivability, but close integration is essential.

6.0 TYPICAL SCENARIOS

This section will describe a possible scenario for a missile attack on a ship, in order to illustrate the various phases of the engagement, and the application of the various weapon systems which can be used for defence. The ship is assumed to be operating in an effectively solitary role, such as conducting ASW operations at some distance from a task force, or escort or patrol duties such as the USS Stark, or being part of a small force such as HMS Sheffield.

We will postulate an attack on the ship by a small force of aircraft carrying anti-ship Exocet missiles. The attackers have learned of the presence of the ship through intelligence and monitoring of communications, and have obtained an approximate fix through use of communications EW and triangulation. The ship is observing radar silence, but is sparingly using communications with other elements of the force and its helicopters. The scenario will be described first for the case where the defence uses hard-kill weapons only, and second where both hard and soft-kill weapons are deployed in the appropriate sequence.

The attackers approach at low level, to remain below the radar horizon of the ship. At a point calculated to be within missile range of the ship, the first attacking aircraft climbs to an altitude where it should be able to see the ship with its search radar. (For a 50-mile range missile, this would be about 2000 feet.) The search radar is activated for a few sector scans only, providing position information on the ship to the attacker. This information is transferred to the Exocet missiles, which are then launched, with a pre-programmed seeker activation range of 10 miles. The missiles boost themselves to a speed of about M1 (10 miles/min.), and head towards the ship using an inertial mid-course guidance system. They descend

to wave-top height, using a radio-altimeter to maintain station. The ship, which received the radar transmissions of the attacker on its ESM receiver and reacted rapidly by switching on the ships search radar, managed to get a fix on the attacking aircraft before it descended below the radar horizon. A brief indication was also obtained of the presence of missiles, before these too went below the radar horizon. The ship activates tracking radars, using the last data obtained on missile position, but cannot obtain a target. Anti-missile missiles are readied, and the ship alters course to allow optimum use of the missiles and reduce radar cross-section to the incoming missile.

Four minutes later, at ten miles, the Exocet seekers are activated and commence a search pattern. The superstructure of the ship, which is visible to the seekers, is detected, and the seekers lock on. The activation of the seekers, their search and then lock-on signals are detected by the ship ESM, which provides positive identification and bearing of the attack. The defensive missile tracking radar has been unable to see the missiles, as they remain below its horizon. Ten seconds later, at eight miles, the tracking radar, cued by the ESM system, detects the incoming missiles and the defensive missiles are launched. The latter, travelling at M3, have difficulty in acquiring the targets due to the small radar cross-section and the clutter resulting from proximity to the waves, and do not pass close enough to detonate. This is observed twelve seconds later, with the incoming Exocets at six miles. Other defensive missiles are fired, but with the worsening clutter and multipath situations, they do no better. The CIWS is armed and the positions and other data on the Exocets, transferred. The first missile comes within range at 3.5 miles and is detected by the Phalanx search radar, but with difficulty due to clutter and multipath. Lock is obtained, again with difficulty, and the tracking noise resulting from the poor lock causes inaccuracies which delay the kill of the missile until it has reached a range of less than 1000 yds. At this point, it is too late to engage the other missile, which impacts the ship.

In the second version of the scenario, the ship is employing soft-kill and hard-kill assets in a coordinated manner. Before the attacking aircraft are anywhere near the force, their arrival is anticipated, and the on-board ECM is readied to produce false targets on search radars. Chaff has been regularly deployed over an area of about 10 miles around the ship. When the attackers pop-up and activate the search radar, the on-board ECM immediately produces synchronized false targets which appear on the radar scope as a number of ship-like echoes. These add to the number of echoes resulting from the chaff previously deployed and the skin echo of the ship. In consequence, when the attacker designates one of the radar targets he sees, he actually designates a false target some six miles from the true ship position, and the Exocet missiles are launched with this position programmed in. As before, the ESM detects the aircraft's search radar and alerts the ship, missiles are readied, and off-board decoys and chaff are prepared and launched. When, at ten miles from the false target's position, the Exocet seekers are activated, a host of realistic targets are detected in search mode, together with jamming. One missile locks on to a chaff cloud, the other decides that one of the decoy

jammers is the target and changes to home-on-jam mode and homes on it. (If it had locked on to the ship, the on-board ECM would be activated in a seduction mode, transferring lock to a decoy or chaff cloud.) Because of the initial incorrect position, the missiles are not heading towards the ship but have a large crossing component, resulting in an increased radar cross-section to search and tracking radars on the ship. Defensive missiles are launched, as it is not yet evident that neither missile is a threat to the ship. One of the Exocets is successfully destroyed by the AMM, the other continues towards its intended target, the decoy jammer, flies underneath it and loses its guidance signal, by which time it is well past the ship.

Both these cases discuss the effect of only one pair of Exocet missiles. With a number of attacking aircraft, many missiles would be launched within a short period. (Soviet doctrine is believed to be based on saturation of defences through multiple missile attacks from different directions.) In the first case scenario, the hard-kill defences would be overwhelmed by the arrival of all missiles, accurately targeted on the ship, with the great difficulty of tracking them due to their small radar cross section head-on, and the multipath effects resulting from the sea-skimming trajectory. In the second case, most of the missiles would be targeted on chaff or false targets. When the seekers are activated, the probability is that most will lock on to chaff or decoys. With initial position errors resulting from the distraction targeting, the missiles are easier to detect and track by radar and engage with AMMs or CIWS if they present a threat to the ship. Those that lock on the ship can also be attacked with on-board seduction jamming or breaklock techniques, through seduction chaff, or seduction decoys.

It is clear from this fairly typical scenario that a combination of soft and hard-kill weapons is much more effective at ensuring the survivability of the ship than guns or missiles alone. For maximum effectiveness, however, the weapons must be well coordinated. The use of on-board ECM in the distraction mode, together with pre-sown chaff, can very much reduce the likelihood of the ship being targeted correctly by the attackers. This means that most of the ASMs launched head for the wrong place, making them more detectable to the defence, and increasing the probability of engaging them with AMMs in the mid-course phase. Those that survive will have an unfavourable geometry for detecting the target when their seekers are activated, making them vulnerable to deception by chaff, decoys and on-board ECM when attempting to acquire the target. Attacking missiles which leak through this layer (by successfully locking on to the ship), can then be engaged by AMMs, by on-board ECM using seduction techniques, by combinations of active on-board ECM and off-board decoys and chaff, and, in the last resort, by the CIWS. The command and control system (or TEWA - threat evaluation and weapon assignment) must absorb all the data coming from the various sensors, (principally ESM and radar, but including IR, sonar and visual, if available), decide at each stage which defensive weapon is required and make the appropriate assignment, monitor the results, and act accordingly.

The majority of present day ASMs are radar guided, with a self contained seeker head on board. There are also command-guided missiles, and missiles employing radiation from the target for homing purposes. These latter can home on radar signals (anti-radiation missiles or ARMs), on infra-red emissions from hot-spots on the ship, or use the contrast between the infra-red image of the ship and the background. The best countermeasure to ARMs is to turn off the radar which is being used for homing. Infra-red flares can be used to seduce IR seekers away from the ship, and may be combined with chaff to deceive dual-mode seekers.

7.0 POSSIBLE SYSTEM ARCHITECTURES

As we have seen, a ship's captain who has only hard-kill weapons in his arsenal is potentially at great risk. A coordinated, multi-directional attack by a dedicated and sophisticated opponent is quite likely to overwhelm the ship's defences. We have also pointed out that to make soft-kill alternatives credible and practicable requires both:

(i) early detection, classification, and identification of targets
(ii) trustworthy kill assessment for both hard-kill and soft-kill weapons.

With these requirements met, one can use a soft-kill weapon, assess its effectiveness, and still respond with another (possibly hard-kill) alternative if necessary. The commander is now managing the ship's self-defence resources rather than just responding to events. Effective systems integration is the key to realizing this scenario.

7.1 SYSTEM INTERCONNECT TECHNOLOGY OR SYSTEMS ENGINEERING?

When addressing ship's systems integration issues, there has tended to be an over-emphasis on the hardware aspects of the problem at the expense of an overall systems approach which looks at both hardware and software. This can undoubtably be attributed to the fact that "hardware comes first", and that both the hardware and software issues are sufficiently complex as to absorb all of the effort expended on them. In this section we will discuss some of the software aspects of integration which have been, if not unaddressed, at least underaddressed. First though, as there appears to be a growing consensus with regard to data transfer and processor technologies, we will begin by reviewing this material.

Obviously, adequate interconnect technology is needed to provide for ship-wide data transfer between systems. The simplest (and earliest) solution is to provide point-to-point communication lines which serve as high speed dedicated channels. However, reliability requires that redundant lines and/or switches be provided, and the technique is not very flexible. There are now available a number of network options which offer better solutions. Particularly attractive for highly integrated systems, local area networks (LANs) provide a number of advantages over point-to-point including cost (less cabling and fewer interfaces), reconfigurability, and flexibility.

Survivability/reliability requirements can be met by providing several redundant networks and switches to allow several data paths between any two systems. Examples of possible LAN options are token bus systems such as IEEE 802.4, token rings (IEEE 802.5) and the SHINPADS system being used on Canadian ships. For future R&D, options which can be emulated with available commercial equipment such as Ethernet (IEEE 802.3) have a slight advantage in that cheaper commercial quality equipment can be used for prototyping and ADM development, with Mil Spec equipment being phased in for STM system development. Other options include the use of fiber optic technology (FDDI - Fiber Distributed Data Interface) and broadband networks which allow point-to-point communication channels to be synthesized dynamically.

With regard to processor technology, most current systems are based on centralized configurations using one or more minicomputers. For computationally intensive applications several minicomputers may be combined by employing pipelined or master/slave relationships. Reliability/survivability for critical systems is provided by a "hot backup" system which can be switched in when needed. However, the next generation of processors will almost certainly be based on powerful 32-bit microprocessors (e.g. MC68030 or Intel 80386) configured either as embedded systems or as single board computers complete with memory and required interfaces. Where more processing capacity is needed, multiprocessors built around standard bus systems (e.g. VME or Multibus II) are the likely solution. A new generation of RISC (Reduced Instruction Set Computers) microprocessors such as the MC88000 promise even more performance gains in the near future.

The use of improved VLSI design techniques such as silicon compilers has added a new element to the design equation. Complex ASICs (Application Specific Integrated Circuits), can be designed, simulated, and produced in much less than a year. ASICs have the disadvantage that they limit flexibility by committing the design to a particular solution approach. On the plus side, they can implement specific algorithms several orders of magnitude faster that the most carefully crafted assembly code running on a general purpose microprocessor. The rapid turn-around time makes it possible to correct or improve faulty designs within the normal time-frame for most projects. Used wisely, they place a powerful new tool in the hands of system designers.

In summary, a hardware view of the next-generation Command and Control system is likely to resemble the architecture pictured in Figure 5. It will consist of one or more LANs, with appropriate network gateways where required to connect to other ship's systems such as navigation. The actual bus architecture used for any particular ship will depend on the LAN technology chosen and expected data transfer requirements. Individual subsystems may have embedded micro- or multiprocessors; additional multiprocessor stations will be available to handle Command and Control functions, or to off-load computationally demanding tasks from individual subsystems.

So, on the hardware side, great progress has been made towards integrating sensor/weapons subsystems while at the same time decentralizing the computational workload. Unfortunately, the software view of many systems

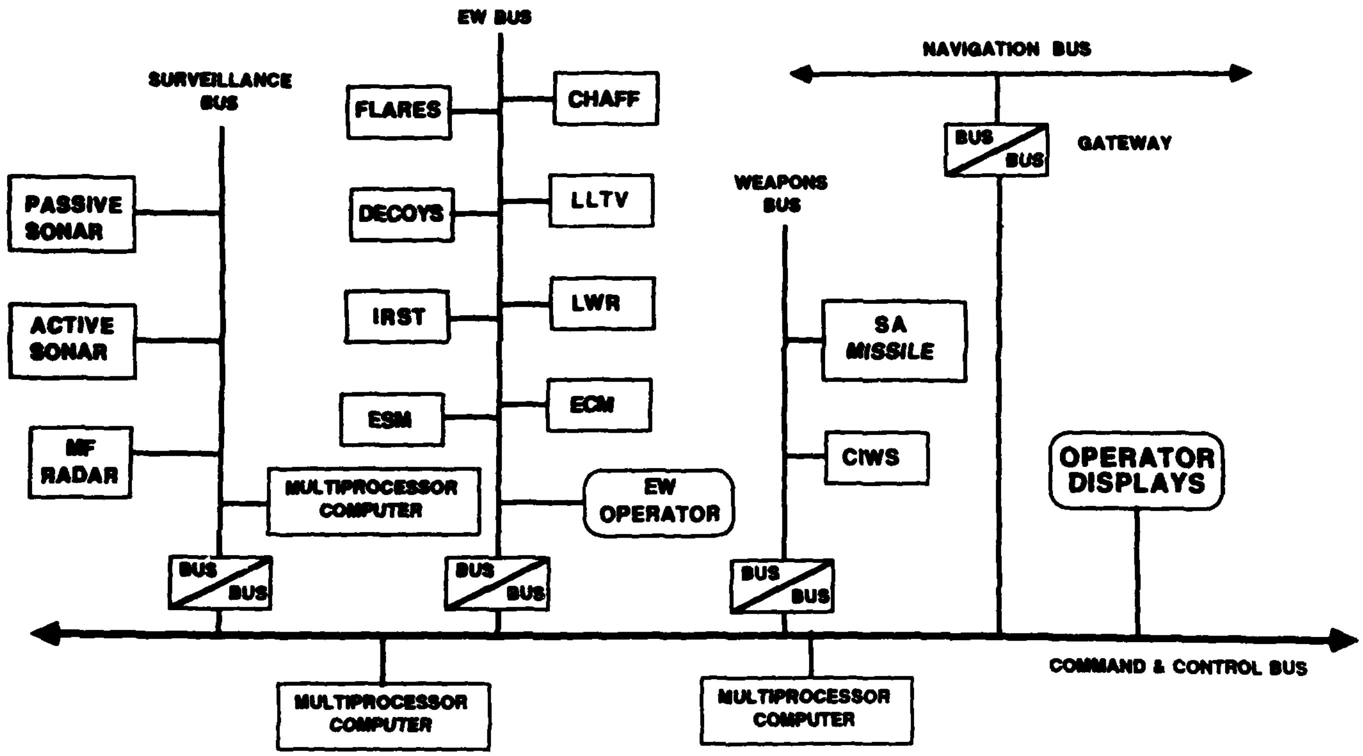

FIGURE 5 ARCHITECTURE OF NEXT-GENERATION COMMAND & CONTROL SYSTEM

currently being designed looks more like Figure 6 than Figure 5. Many of the apparent gains promised by a distributed hardware architecture remain ephemeral due to software and systems designs which do not capitalize on the opportunities provided. In effect, the same systems architectures used for the last generation minicomputer/point-to-point connected systems will have been overlaid on the new distributed hardware. Conceptually, the system is unchanged: although new hardware technology by itself will bring some performance improvements, the real potential is still unrealized.

Seen in this light, it is apparent that current state-of-the art systems such as Aegis are not revolutionary but evolutionary in their design. As noted, they are physically distributed but still highly integrated and centralized with regard to information and data flow. Low-level data from sensors (mainly radar) is transferred to the Command and Control system and processed there. Threat evaluation and engagement solutions are performed by the C&C system, which then assigns targets and sends low-level directions to the various weapons systems. Managing soft-kill weapons is dealt with almost as an afterthought.

Conservative approaches to designing the next generation improvements for these systems tend to focus on finding ways to improve the performance of individual subcomponents such as the radar and hard-kill systems. For example, using other sensors such as IRST to cue the radar, which could then be more directional and hence get more energy on its targets, provides a response to low RCS targets. These solutions offer another evolutionary step, as opposed to a more revolutionary approach aimed at achieving true synergistic sensor integration and hard-kill/soft-kill coordination.

To use the terminology developed in section 4.0 (Integration of Sensor Data), in order to achieve improved hard-kill the main emphasis is on track correlation, which does not require the same level of integration as track identification. If hard-kill is the preferred strategy, making a specific target identification becomes a low priority task; one needs only to know the target location and that it is threatening. Engagement decisions are straightforward: one or more intercepts are attempted with an anti-missile missile, and if this fails, the target is engaged with a CIWS. The main integration problem stems from multi-target raids and false alarms, i.e. making sure that all targets are engaged as far as possible without ammunition being wasted or friendly platforms shot down.

Of course, we have argued in this paper that the strategy of reliance on hard-kill is inherently flawed, and that a coordinated defence using all of the ship's resources is preferable. As was pointed out in the introduction to this section, to implement such a policy requires early detection, classification, and identification of targets, as well as trustworthy kill assessment for both hard-kill and soft-kill weapons. As we saw in section 4.0, to achieve these goals we need true synergistic sensor and weapons integration. Such a system would be revolutionary rather than evolutionary in its design, requiring that sensors and weapons become intelligent subsystems capable of working cooperatively with the Command & Control system.

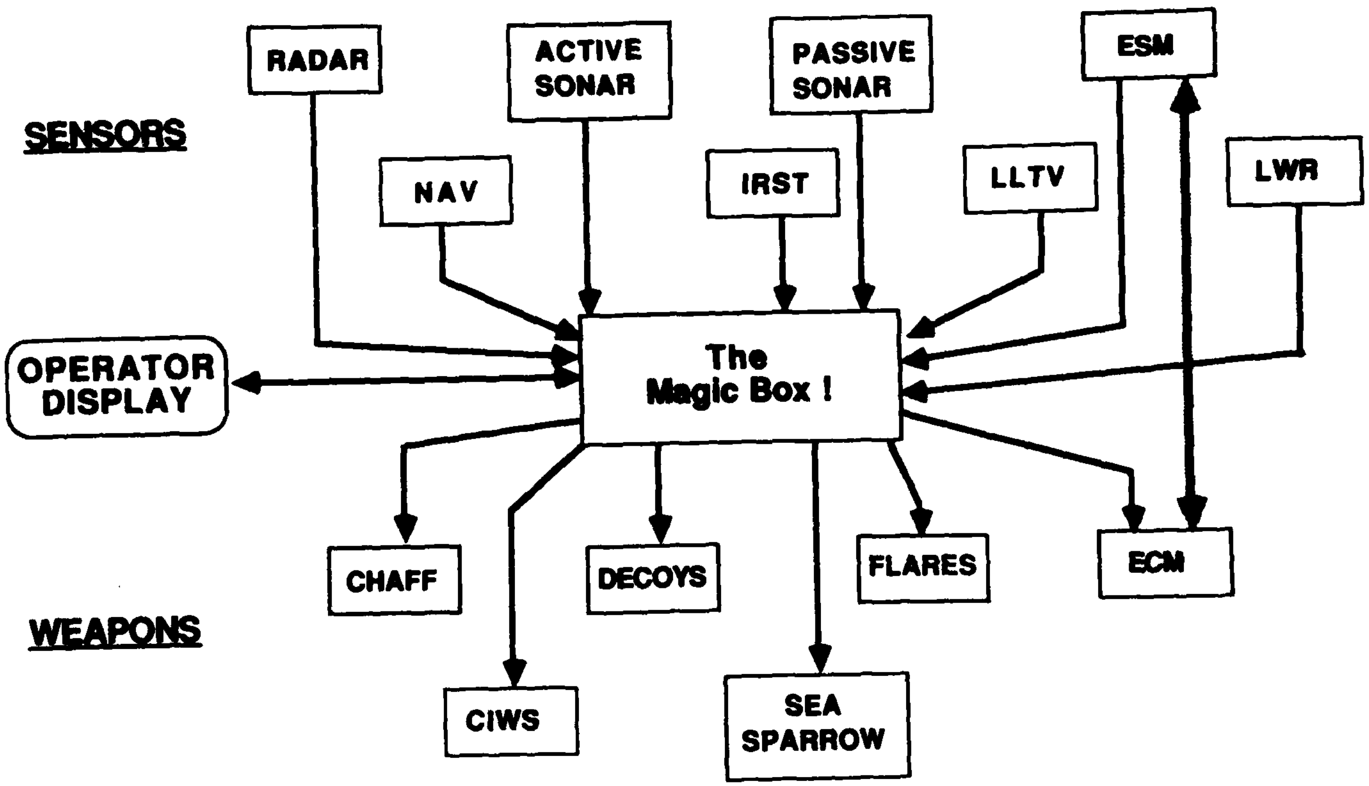

FIGURE 6 ARCHITECTURE OF CURRENT DESIGNS OF COMMAND & CONTROL SYSTEMS

One might well ask the question: If this is so obviously the right approach, why haven't such systems been built? As is noted below, there has been at least one attempt to build such a system, and the designers clearly recognized the basic need for the new architecture. This case apart, the answer is a combination of reasons, including rivalry and compartmentalization between the various systems, to the point that, unfortunately, there is still no consensus as to how to design intelligent, distributed, cooperative systems. However, a number of pertinent model prototypes have been built by researchers working in the area of Artificial Intelligence, and while they are still laboratory artifacts, they do work. The most promising design approaches use actor-based and object-oriented techniques to, in effect, build a software system which models a group of cooperating human experts. The challenge now is to take this technology out of the laboratory and put it to work, making the compromises necessary to achieve real-world performance goals as required.

7.2 A FIRST ATTEMPT - SENIT

One of the first to recognize the problem discussed in this document and to attempt a solution were the French navy with the SENIT system. In the mid-70s a system for integrating the EW equipment on the Tourville and Georges Leygues class ships was proposed, developed and tested. This system integrated the ESM, on-board ECM, and decoy launchers. A second generation, was subsequently developed for an anti-aircraft corvette: this system also integrated ESM receivers, on-board ECM, and two types of decoy launchers. Provision was also made for coordination of the 100 mm gun and SADRAL weapon system. A federated computer control architecture was used. These systems provided the opportunity to recognize the need for and to develop algorithms for managing the outputs of the various systems, manipulating these to select appropriate sequences of action, and commanding the defensive assets accordingly. It also became rapidly evident that fully automatic operation was essential if adequate response time was to be obtained. (This has since been demonstrated with the Sheffield and Stark incidents.) Lessons learned in these projects were that managing the complementary use of hard and soft-kill-sub-systems requires automation of the two sub-systems and their concurrent design by the same people. Fully automatic operation of the EW systems was also found to be essential, if the required reaction times were to be obtained.

8.0 ISSUES TO BE ADDRESSED

8.1 OBTAINING REQUIRED CAPABILITY AND PERFORMANCE

The principal challenge in the research area is to come up with a set of algorithms which will coordinate the sensors and weapons on the ship in the optimum manner for all types of attack scenario and geometry envisaged. Before these can be written, it will be necessary to obtain a far greater understanding than presently exists of the means for integrating data from different types of sensors and both hard-kill and soft-kill weapons systems, and determining the effectiveness of various types of soft-kill systems when working in combination. Present understanding is limited to estimating the probability of success for the use of chaff under certain conditions, with and without a helicopter-borne decoy. There are few figures for effectiveness of ECM techniques, with or without chaff or decoys. There are few figures for effectiveness of off-board decoys, expendable or manoeuvrable. A substantial program of computer simulation is required to come up with these figures, which are a prerequisite for proceeding to the design of algorithms for using the defences in combination.

8.2 FEEDBACK

This concept has been mentioned several times earlier in this paper, in the context of determining during an engagement whether the particular weapon engaging the attacking missile at any instant is being effective and whether the engagement can be broken off or needs to be prosecuted. For hard-kill weapons, it is clearly undesirable to continue to pour rounds into an attacking missile which has already been disabled, or to fire additional salvoes of anti-missile missiles when earlier shots have achieved their objective. This is particularly true due to the expendable nature of hard-kill weapons; the limited number of rounds that can be carried and the need to reload, together with limited life of gun barrels, factors which can result in there being no weapons available at later stages of a protracted engagement if supplies are not conserved. The same applies to soft-kill weapons such as chaff and expendable decoys, which are also carried in limited quantities and require reloading into launchers.

In the case of ECM, the situation is somewhat different. Here there is no question of expendability - the ECM system can be used over and over again. However, any on-board ECM system has limited capacity for handling multiple simultaneous attacks, and there may be a need to try more than one countermeasures technique before finding one that is effective against the particular missile being attacked. These factors make it imperative that only those missiles that are suceptible to being defeated by on-board ECM be assigned to the ECM, and that the ECM system be provided with data to help it decide whether or not the particular countermeasure being used is deflecting the missile from its target. Modern ECM sets contain means for determining whether the missile emitting the radar signal being jammed has ceased to move towards the ship. Unfortunately, these means can provide ambiguous indications under certain conditions, and supporting evidence from precision systems such as radar, IRST, or optical tracker could be of great value. Research is

required to determine how to improve the reliability of this 'kill' assessment, and to coordinate and integrate the information produced by it with other sensors which could improve the accuracy.

8.3 FLEXIBILITY AND CAPABILITY FOR EXPANSION

It is important in designing a system which integrates sensors and controls hard and soft-kill assets to avoid building in predictable responses which might be rendered ineffective through changes in tactics (both friendly and enemy), or by the introduction of new missiles. This might be regarded as the difference between a "table look-up" approach as compared with an "intelligent assistant" approach. In keeping with this philosophy, it is essential that allowances be made in the design for the addition of new sensors or getting more accurate data from existing ones, and for the introduction of new algorithms.

To meet these requirements, the next generation of self-defence systems must be designed to facilitate change and growth. Monolithic architectures must be replaced by designs based on small loosely-coupled building blocks which encapsulate functions, and which can be assembled and re-assembled as needed to provide the overall functionality required. Software will likely be the key to achieving (or failing to achieve) the desired modularity. The past decade has seen a great deal of research aimed at developing new software engineering concepts which result in truly re-useable software components. Noteworthy amongst these are the ideas of abstract data types (information hiding), object-oriented design and programming techniques, the use of hierarchical or layered design concepts, software development environments, and rapid prototyping approaches. (Ref 1.)

8.4 WAR MODES OF OPERATION

There is some evidence that many Soviet radars, including missile seekers, are equipped with means for switching to special war modes in the event of hostilities. These modes involve transmission at frequencies only rarely used in peacetime, and hence they may not be included in the emitter databases employed in ESM and ECM systems. If such emitters are encountered during an engagement, they may not be correctly recognized by the EW systems, at least at first, and this may delay recognition of the platform and of the selection of the optimum countermeasure to be used by the ECM. In a worst case, it may be necessary for the ECM set to fall back on a generic countermeasure, rather than use one which exploits known weaknesses of the particular threat. It is important that this situation be allowed for in the design of the Command & Control system.

Defensive weapons normally have a fully automatic mode, in which they acquire the target and perform their intended function without any manual intervention. In the case of systems designed for operation in the terminal phase of an attack, this mode is vital, as time is not available for manual reaction. This applies to on-board ECM systems, short-range AMMs, and CIWS.

An alternative mode is semi-automatic, in which the system goes through all required steps with the exception of the final one of transmitting a jamming signal or opening fire. However, the target is being tracked and a response is possible within milliseconds of manual approval being given. In peacetime, this would normally be the mode adopted, to avoid the possibility of inadvertently shooting at a friendly aircraft or of jamming a friendly radar at an inopportune moment. There is also the need to not disclose to a potential enemy countermeasures responses that are available - a well-known technique is to stimulate an ECM system with a signal it recognizes as a threat and to observe the response. However, when the ship is in danger of a possible attack, it is vital that all defensive systems are in a mode where they can react in a timely fashion if needed, and this normally means automatic mode. (Under favourable circumstances, some current anti-ship missiles can be launched in such a manner that the homing seeker is only activated when the weapon is ten seconds from impact.)

In the event of damage to the ship, defensive weapons may be required to operate in degraded and independent modes, with manual input and activation. ECM, chaff and CIWS systems are capable of this type of operation, requiring only a manual input of threat bearing.

8.5 IMPACT ON EW, SENSOR AND WEAPONS SYSTEM DESIGN

One of the effects of the approach advocated in this document, of coordinating sensor integration and the control of defensive assets, is to force consideration of the integration of the various assets themselves. Hitherto, the various systems have been specified, procured and installed as individual systems, with only minimal concern for interoperability. In the case of some systems (typically ESM and on-board ECM), some attempt is made to interconnect, but usually only in one direction (e.g. the ESM system can pass director information directly to the ECM system). The only concern for interoperability has been that of EMI/EMC. Once it is realised that data from various sensors must be integrated to be effective, consideration can be given in the design of the sensors to maximizing overall performance, rather than individual system performance. This may involve matching or complementing sensitivities and fields of view. It may involve the actual integration of the various receiver and transmitter apertures, and even the transmitter power amplifiers themselves.

8.6 RESEARCH REQUIREMENTS

Summarizing where we are: we have described the "generic" sensor/weapons suite, laid out some basic principles for integrating systems, and illustrated the advantages of the fully integrated "synergistic" concepts with feedback over the more evolutionary "one-way" data flow models. We have also made the case (at least implicitly) that current efforts are not going to solve this problem because their focus is too narrow, probably out of necessity as they are aimed at short-term solutions. Also, as we know from experience in the EW field (e.g. with CANEWS), borrowing technology from abroad and assimilating/enhancing it is a sound approach, but buying "off-the-shelf" solutions tailored for someone else's problems just doesn't work.

Consequently, it is proposed that the first order of business is to get some hands-on experience with these issues. One option is a Systems Engineering Testbed as illustrated in Figure 7. This is basically an enhanced version of an ESM testbed used to develop an "Advanced Modular ESM Processor" (Ref 2), extended to include other sensors, and adding a Command and Control function and weapons models. It would be intended as a high fidelity simulation which could be used to implement integration strategies in a realistic environment to help identify problem areas and test possible solutions. The key point to make is that, unlike older simulation methodologies with their well-known deficiencies (Ref 3), the intention for the integration testbed is that it could eventually "grow" into a prototype for a real system. Along the way many of the R&D concerns would be exposed and explored; if nothing else at the end of the day we would at least understand the problems even if they hadn't been solved.

Before embarking on such an effort, a thorough engineering study aimed at systems/threats/requirements analysis needs to be undertaken. An important part of this is response time analysis - there is a need to understand the timing constraints in real situations, e.g. how much time does it take to recognize the midcourse guidance mode of a missile seeker, transfer that information to an ECM set, and how long does the ECM need to effectively implement the appropriate countermeasure(s). Is there enough time? The same analyses obviously need to be applied to decoys, chaff, flares, etc. At the present time, the hard-kill community has a much better understanding of the timing constraints involved in using their weapons than the soft-kill world does, so information on hard-kill should be readily available. With some notion of required response times in hand, alternative integration concepts can be defined and analyzed.

A key problem organizationally is that the responsibility for the various hard and soft-kill systems is divided among separate agencies (often geographically separated) throughout all phases of the research, development, and procurement processes. A way must be found to pool this expertise if the larger issues are to be addressed. At the very minimum, a systems integration research program needs specialists knowledgable in the four basic sensors, soft-kill and hard-kill weapons, as well as Command and Control systems. It will likely be necessary to further develop our existing expertise in several of these areas; Canadian experience with the NAAWS program could be invaluable in this regard. If the scope of the work proves to be too ambitious, an alternative might be to concentrate on integrating EW soft-kill assets with EW sensors. Even for this more limited undertaking, it is apparent that close cooperation with the radar, IR, and Command and Control communities is essential.

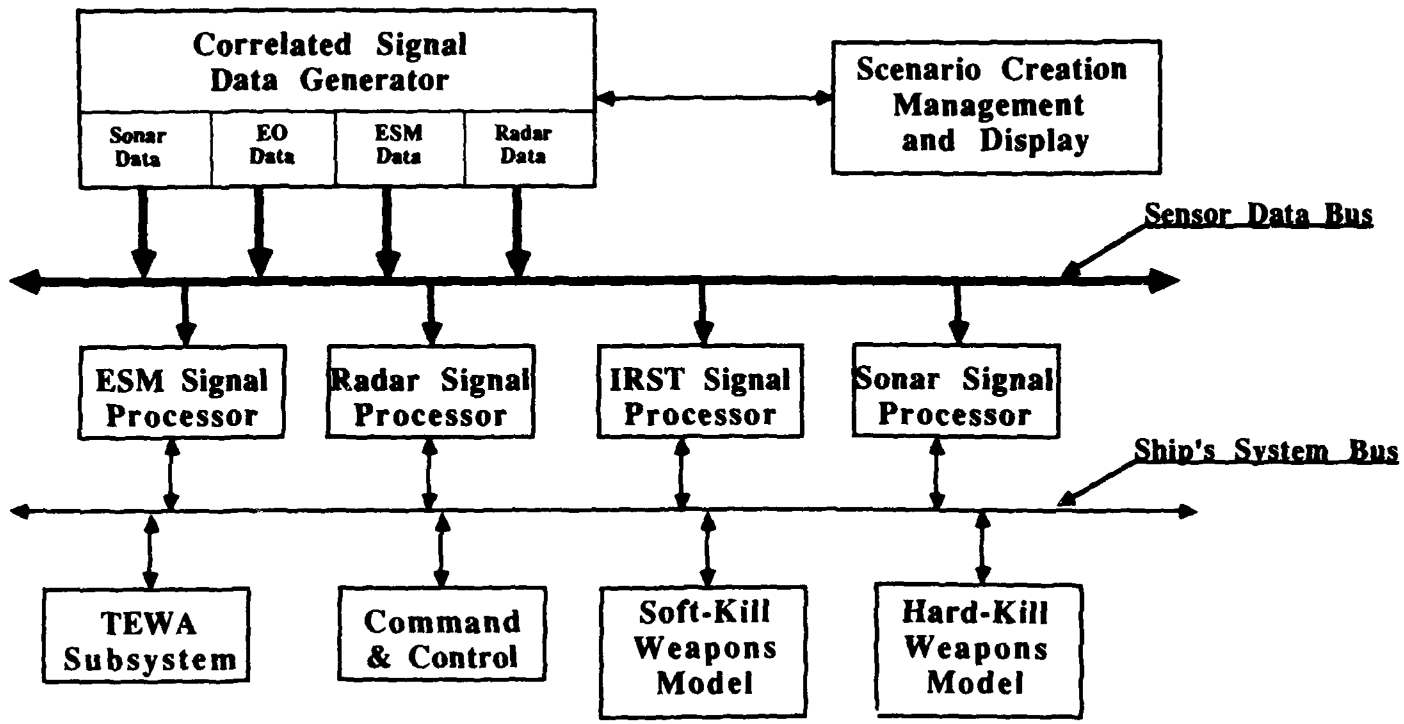

FIGURE 7 SHIP'S SYSTEMS INTEGRATION TESTBED

9.0 CONCLUSIONS

The operational requirement for a program of research and development as proposed in the last section is clear and pressing. We believe that the examples presented in this paper are convincing evidence that, without such a program, we run a serious risk that it may not be possible to defend our surface ships against tomorrow's threats. It is unrealistic to expect that our friends and allies, each with their own particular set of needs and constraints, will provide us with "off the shelf" self-defence systems which adequately address uniquely Canadian requirements.

The first step is to achieve a sufficiently clear understanding of the problem so that the technology needed to solve it can be identified. Already, we can see that the hardware required to implement an integrated ship is now or will soon be available; what is lacking is a system design concept for achieving this goal and the means for translating it into software. Promising technology has been developed in university research laboratories and elsewhere and is potentially available. Some military experience has already been obtained. The challenge now is to bring together the skills and talent necessary to press ahead with a clearly focused, cooperative effort aimed at realizing the fully integrated ship.

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In order to defend a ship against an attack by anti-ship missiles, it is necessary for the ship to detect the attacking forces, and then to use its entire defensive suite of weapons. These weapons may consist of anti-missile and anti-aircraft missiles, gatling guns, and electronic countermeasures such as on-board jammers, off-board decoys, and chaff. To maximize the probability of detecting and identifying the attacking forces and the missiles launched against the ship, information from all of the ship's sensors must be integrated. Similarly, if the chances of defeating the incoming missile attack are to be maximized, the defensive weapons must be deployed in a sequential and co-ordinated manner, in a layered defence.

This paper discusses the advantages to be obtained from the integration of sensor data and the co-ordination of hard-kill (missiles, guns) and soft-kill (ECM, decoys,, chaff) weapons systems. Problems of integration of information from different sensors, the need for a layered defence, the characteristics of the various systems, a typical scenario to illustrate the need for integration, possible architectures and issues that must be addressed are examined. The approach is from the viewpoint of Electronic Warfare, but encompasses all aspects of the sensors and weapons available.

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